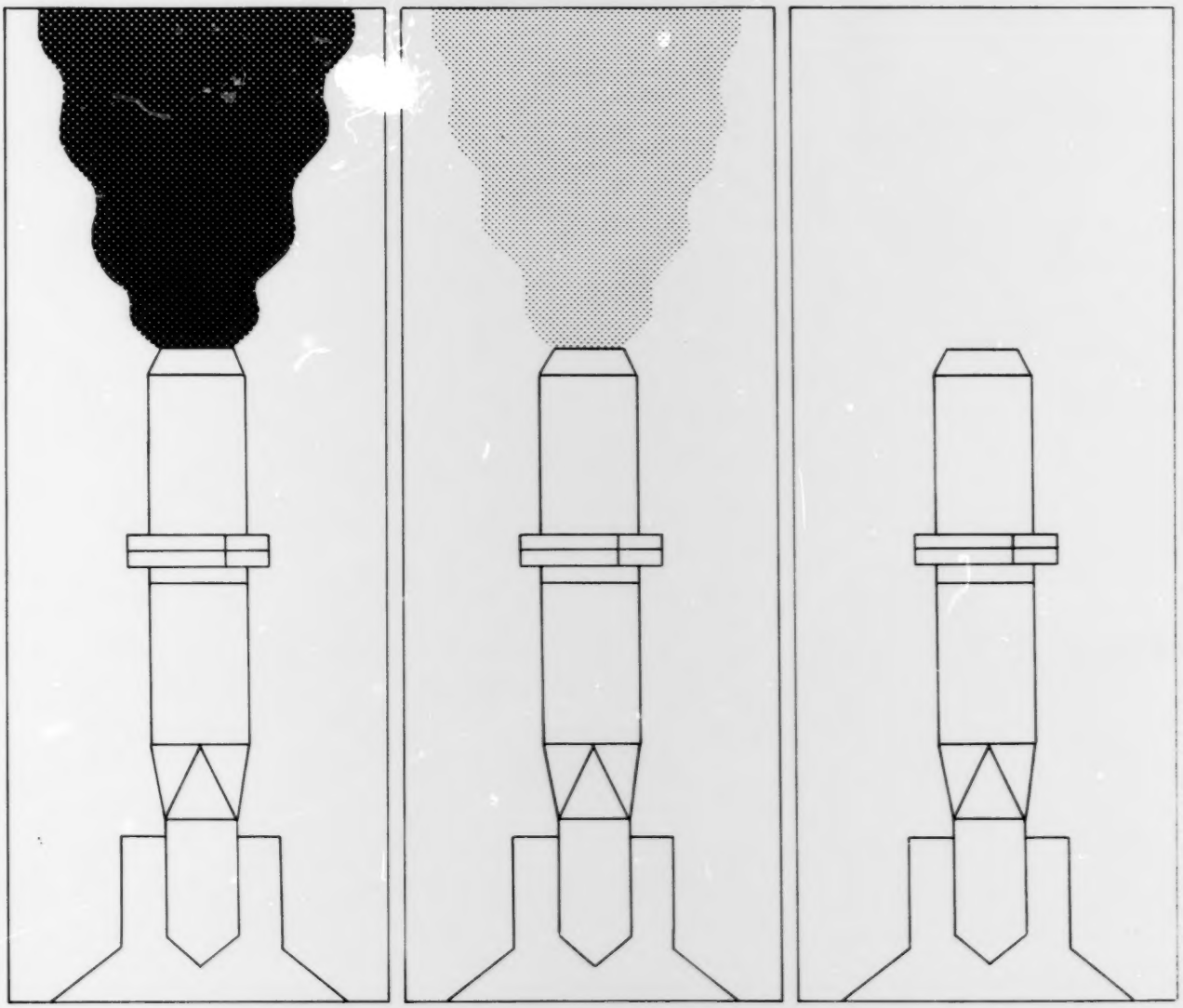
Summary Report for a Test Burn of Chlorophenol Contaminated Wood Wastes at Northwood Pulp Mill, Prince George, B.C.

July, 1989



Province of British Columbia
Ministry of Environment

Environment Canada
Environnement Canada

A TEST BURN OF CHLOROPHENOL CONTAMINATED WOOD WASTES AT NORTHWOOD PULP MILL PRINCE GEORGE, B.C.

SUMMARY REPORT

A joint project conducted by:

Environment Canada
and
Ministry of Environment of British Columbia

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ABSTRACT

Environment Canada and British Columbia Ministry of Environment conducted a series of tests on an industrial woodwaste (hog fuel) fired boiler at Northwood Pulp and Timber Ltd., Prince George, B.C. The test burn was designed to determine the capability of this combustion system to destroy low levels of chlorophenols, dioxins and furans that sometimes contaminate hog fuel. The test burns, completed in September, 1987 involved the following conditions by burning:

(1) hog fuel specially acquired without adding chlorophenol solution;

(2) hog fuel with chlorophenol solution added at a nominal concentration of 50 µg/g;

(3) hog fuel with chlorophenol solution at a nominal concentration of 400 µg/g.

Ambient air quality was monitored concurrently during the days of testing. During all test conditions the boiler was maintained at constant steam production of about 100 tonnes per hour, or about 60% of maximum continuous rating. The findings were significant. The operating conditions of the boiler resulted in high destruction efficiencies of chlorophenols, dioxins and furans. The lowest destruction efficiency of dioxins and furans was 99.9993% and for chlorophenols, 99.9917% when chlorophenol solutions were added. These destruction efficiencies occurred at an estimated minimum furnace temperature of about 920°C and combustion gas residence time of approximately 3 seconds. Dioxins and furans in ambient air were non-detectable during all test conditions.

RÉSUMÉ

Environnement Canada et le ministère de l'Environnement de la Colombie-Britannique ont effectué une série d'essais sur une chaudière alimentée avec des déchets de bois industriels, de la Northwood Pulp and Timber Ltd., de Prince-George (C.-B.). Ces essais de combustion ont été conçus afin de déterminer dans quelle mesure ce système de combustion permet de détruire les chlorophénols, les dioxines et les furanes que l'on retrouve parfois en faibles concentrations dans les déchets de bois. Ces essais, qui ont pris fin en septembre 1987, comportaient la combustion:

(1) de déchets de bois auxquels aucune solution de chlorophénols n'avait été ajouteé;

(2) de déchets de bois auxquels une solution de chlorophénols avait été ajoutée à une concentration nominale de 50 ug/g;

(3) de déchets de bois auxquels une solution de chlorophénols avait été ajoutée à une concentration nominale de 400 ug/g;

Nous avons contrôlé simultanément la qualité de l'air ambiant au cours des essais. Pendant tous les essais, la production de vapeur de la chaudière a été maintenue constante à environ 100 tonnes/heure, ce qui correspond approximativement à 60% de la production maximale en continu. Nous avons obtenu d'importants résultats. Dans les conditions de fonctionnement de la chaudière, l'efficacité de destruction des chlorophénols, des dioxines et des furanes était très élevée. L'efficacité de destruction minimale était de 99,9993% dans le cas des dioxines et des furanes et de 99,9917% dans le cas des chlorophénols lorsque des solutions de chlorophénols avaient été ajoutées. Ces efficacités ont été mesurées à une température minimum d'environ 920°C et à une temps de résidence des gaz de combustion d'approximativement trois secondes. Nous n'avons décelé ni dioxines ni furanes dans l'air ambiant tout au cours des essais.

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1 INTRODUCTION

The forest products industry in British Columbia uses chlorophenol based chemicals to protect lumber against sapstain and fungi growth. Planer shavings and trim ends which are contaminated with these chemicals are sometimes mixed with other wood wastes burned in hog fuel boilers. When combustion conditions are inadequate there is a possibility of forming chlorophenol dimers such as polychlorinated dibenzodioxins ("dioxins" or PCDDs) and polychlorinated dibenzofurans ("furans" or PCDFs). Another concern is the presence of trace quantities of PCDDs and PCDFs as residual products in commercial chlorophenol solution formulations. These may not be destroyed when combustion conditions are inadequate.

In view of the potential formation of these toxic substances, and the possibility of residual dioxins and furans in chlorophenol solutions not being destroyed, the industry, the public and plant workers have raised concerns about the industrial safety and environmental impact of this practice. Due to lack of published information, the B.C. Ministry of Environment, Environment Canada and Northwood Pulp and Timber Ltd. undertook a joint test program to address these concerns.

The primary objectives of this test program were to evaluate the capability of a modern hog fuel power boiler to destroy low levels of chlorophenols, dioxins and furans as well as assess the impact on ambient air quality.

This report highlights the most significant findings, conclusions and recommendations of this project. Details of the test program, boiler description, sampling and monitoring protocols, sampling and monitoring data and assessment of test results are presented in Volume 2, the contents of which are outlined in Appendix B. Copies of Volume 2 may be obtained from the Ministry of Environment of B.C. or Environment Canada, Pacific and Yukon Region.

2 PLANT DESCRIPTION

Northwood's No. 4 power boiler, used as the test facility in this study, is a water-cooled furnace installed in 1981. Hog fuel is the primary source of fuel but natural gas or oil can also be used. It is designed to produce 170 tonnes/hour of steam when burning 56.9 tonnes/hour of hog fuel with a heating value of 10 750 kJ/kg.

The principal plant facilities, as shown in Figure 1, consist of:

- o hog fuel storage area;
- o distribution conveyor system with five screw feeders;
- o water-cooled furnace;
- o superheater/economizer;
- o viscodyne;
- o primary and secondary dust collection system and a stack.

Related equipment includes:

- o primary and secondary combustion air supply systems;
- o a wet ash removal system;
- o instrumentation and controls.

Hog fuel is delivered to the plant from various sawmills. Oversized materials are removed by a mechanical screen. A distribution conveyor moves the sorted hog fuel to five hoppers. The flow rate of hog fuel from the hoppers to the pneumatic injectors is controlled by screw feeders. Hog fuel is injected evenly over the grate

surface of the boiler. The smaller fuel particles are burned in suspension while the larger wood wastes fall to the grate to form an active layer of burning fuel.

Combustion air is supplied to the furnace by a variable speed, forced draft fan. Preheated air is directed to wind boxes which split the flow to the grate and the firebox.

Flue gases from the boiler pass through a viscodyne, a two-stage multi-clone particulate removal system and then drawn through an induced fan into a stack.

Bottom ash from the boiler is discharged into a water-filled quench tank. Hot fly ash from the viscodyne and multi-clone hoppers are flushed with water to the ash transfer conveyor. The ash is transferred to the bunker storage pit and hauled to the Company's industrial landfill.

3 TEST PROGRAM APPROACH AND PLANT MODIFICATIONS

3.1 Approach

The test program was based on a project plan designed by the Ministry of Environment of British Columbia and Environment Canada. The plan evolved over a period of months during on-site visits and discussions with plant operators. The final project plan set out the test burn conditions, sampling and analytical approaches, quality assurance measures and personnel deployment.

The No. 4 power boiler was selected because the steam output can be maintained relatively constant and steam swings for the mill could be accommodated within the overall operation of the steam plant. It was important to ensure that tests were conducted at similar operating conditions. Woodbrite-24 was selected as the spiking chlorophenol solution. It contains 16.3 weight percent tetrachlorophenol and 7.7 weight percent pentachlorophenol.

The number of test conditions and parameters to be monitored were largely determined by project cost constraints. The sampling locations are schematically shown in Figure 1.

<u>Sampling of Process Streams</u>

- Hog Fuel - Composite samples of hog fuel were collected for each test run.

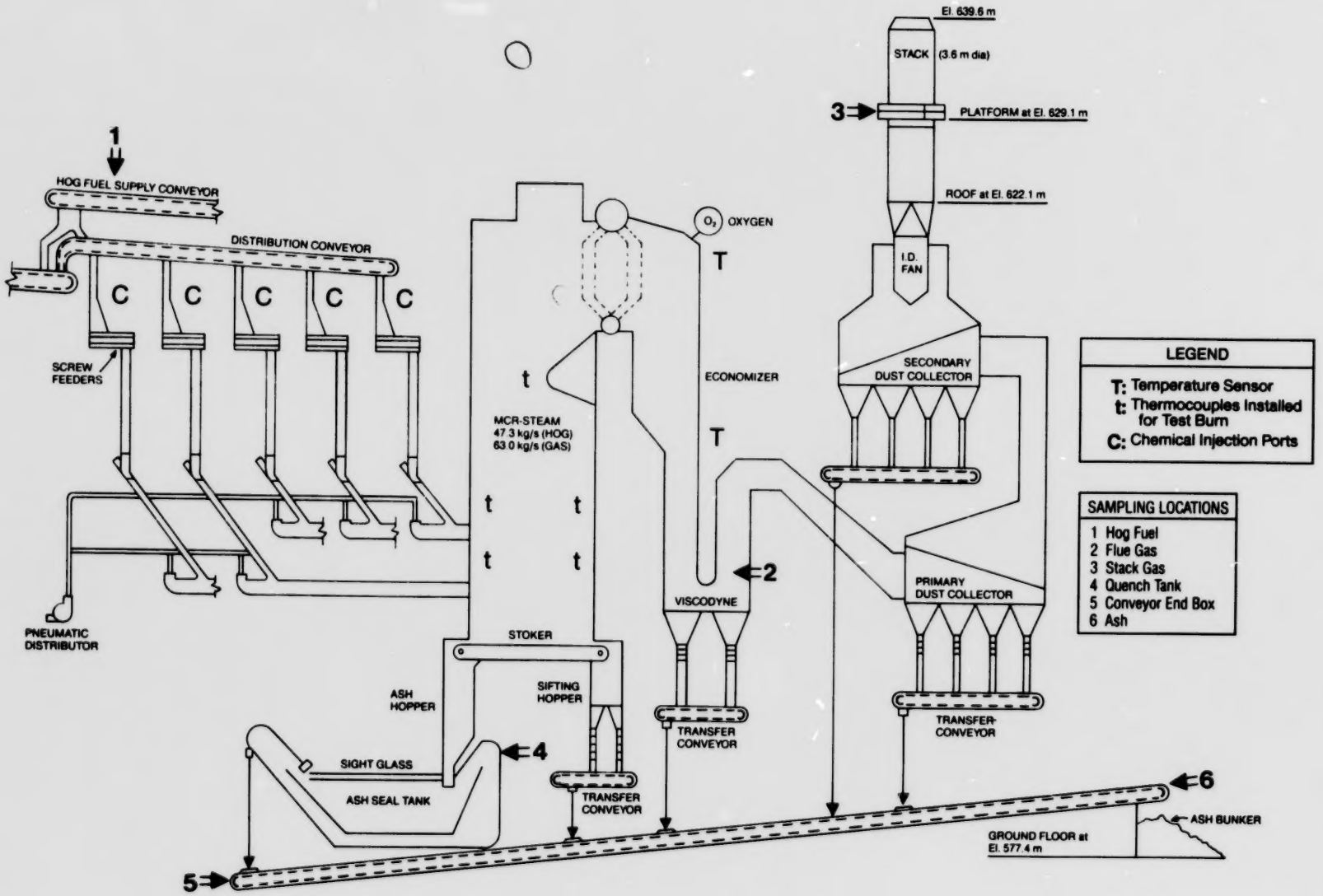


Figure 1: Schematic Diagram of Test Facilities

- Furnace Temperature - Temporary wall-mounted thermocouples were installed at five locations on the boiler. Cost constraints precluded the initial plan to measure temperature profiles across the fire box.
- Flue Gas - A continuous flue gas monitoring system was installed at the viscodyne breeching.
- Process Parameters - Key boiler operating parameters were recorded during the tests.

Sampling of Discharges

- Stack - Isokinetic samples of gaseous, particulate, and organic compounds were collected from the boiler stack.
- Quench Tank - Composite samples of the quench water were collected for the determination of chlorophenols, dioxins and furans.
- Ash - Samples of combined fly ash and bottom ash were collected for the determination of chlorophenols, dioxins and furans.

Ambient Air Monitoring

- Ambient Air Quality - Ambient air stations were installed at 1.9 km north and 1.6 km south of the No. 4 power boiler. Each station was equipped to measure inhalable particulate matter (PM_{10}), total suspended particulate (TSP), dioxins/furans, and polyclyclic aromatic hydrocarbons.
- Meteorological Station - Wind speed and direction were measured at the southern ambient air station.

3.2 Plant Modifications

Some modifications to the boiler and ancillary equipment were required to carry out the tests.

- Chlorophenol Feed System - A chemical feed system was designed to simulate different levels of chlorophenol contamination, As shown in Figure 2, a chemical metering system was used to inject commercial strength chlorophenol solution into the five hog fuel hoppers. It was diluted with water to maximize surface area coverage of the wood chips.
- Furnace Temperature - To determine the temperature profile in the furnace, five temperature probes were installed through the furnace wall. The locations are approximately shown in Figure 1.
- Ash Quench Water - Ash quench water samples were taken from two locations: the quench tank overflow and ash conveyor end box. The quench tank waste water overflow was directed by a chute into a baffled trough and then discharged through a V-notch weir. An automatic sigma sampler pumped approximately half a litre of waste water every minute from the weir overflow.
- Site Facilities - Over fifteen engineers, scientists and technicians were involved in the test burn. Two manual stack sampling trains, five continuous gas monitors and three ambient air monitors were used during the project.

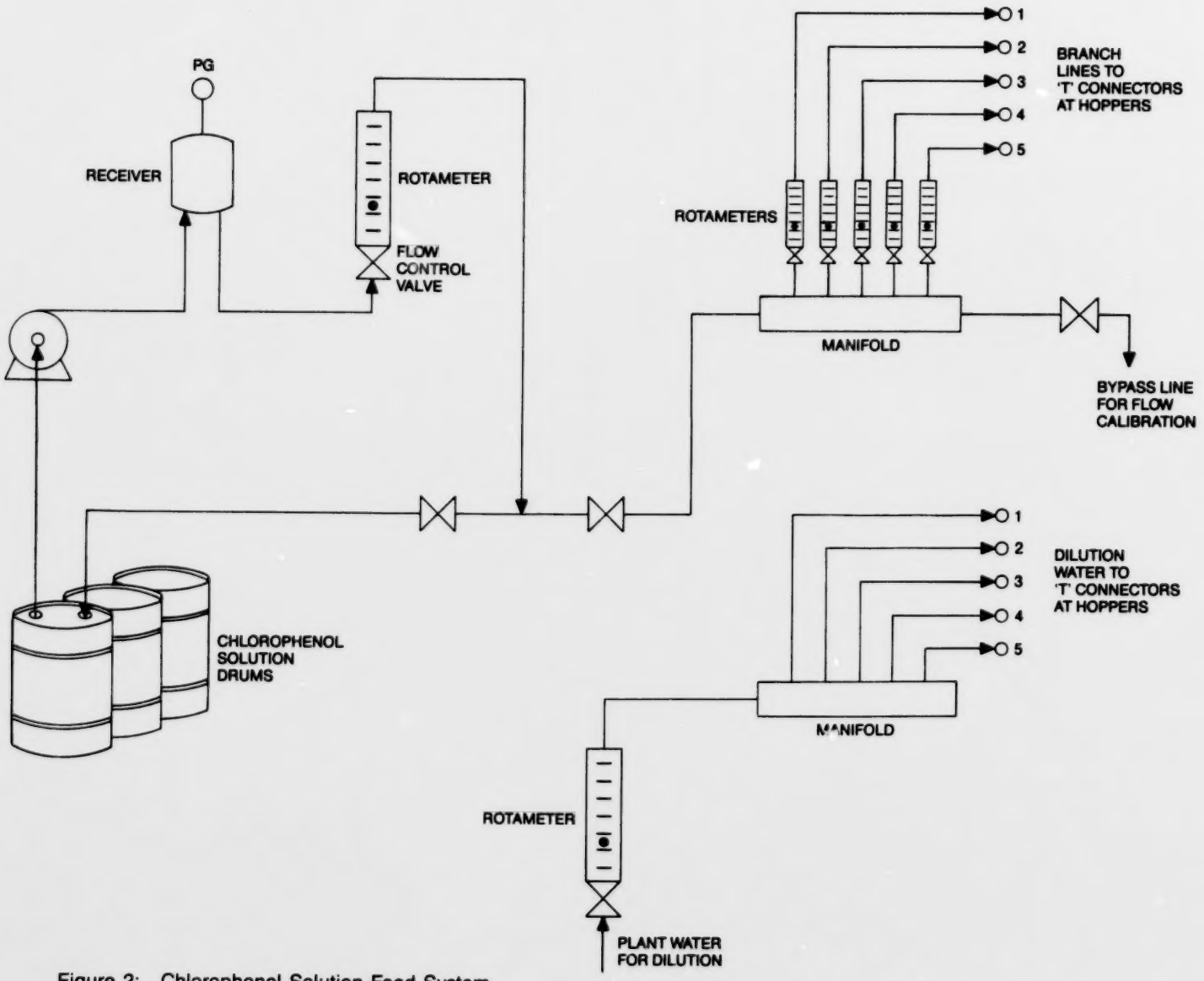


Figure 2: Chlorophenol Solution Feed System

To accommodate laboratory work space for sample recovery and shelter for samplers and personnel, the following provisions were made:

- A 9 square meter shelter was built on the roof for the stack sampling crews;
- Environment Canada's mobile continuious emission monitoring (CEM) trailer housed the continuous in-stack analyzers and a mobile emission laboratory was used for sampling preparation and sample recovery.

4 SAMPLING AND ANALYTICAL PROTOCOLS

Details of the sampling and analytical protocols used during the test burn are presented in Volume 2. Some of the procedures are briefly reviewed in the following sections. Every attempt was made to ensure that approved sampling and analytical procedures were followed.

4.1 Sampling Protocols

Process Stream

- Hog Fuel - Hog fuel samples were taken from the distribution conveyor every 7 minutes. A representative sample of about 34 litres was collected during each run. This was split and transported in special containers for later analysis.
- Flue Gas - Continuous real-time instruments were used to measure the concentrations of carbon monoxide, oxygen, carbon dioxide, nitrogen oxide and total hydrocarbons at the exit of the viscodyne. Samples were withdrawn through a sintered stainless steel filter mounted on the end of a stainless steel probe and then transported through a heated sample line to the sample conditioning system. In the conditioning system, the gas was filtered a second time, then dried before being delivered to the analyzers. The analyzer outputs were fed to a strip chart recorder and to a data logger.

- Process Parameters - Key boiler operating parameters, including hog fuel rate, steam flow, steam pressure and temperature, flue gas temperature, gas burner flow, total and underfire air, percent oxygen and stack particulate concentration were taken from the computer system in the control room and manually recorded every 15 minutes.

Discharges

- Stack - During the test burns, manual sampling for particulates and selected organic compounds in the flue gas was conducted using two simultaneous stack sampling trains at the stack. Figure 3 is a schematic diagram of the sampling trains used for this project. In general, each train consisted of the following components:
  - a specially sized goose-neck nozzle;
  - a heated probe;
  - a heated filter assembly;
  - a series of impingers with various reagents, contained in an ice bath; and
  - a sample case containing controls and the sampling pump.

  Stack gas samples were collected by sampling isokinetically at each of the 48 traverse points. Total sampling period was about 4 hours for each run.

  Particulates were collected on a glass fibre filter and the chlorides and chlorophenols were absorbed with 0.1 N NaOH scrubbing solution in the back half of the sampling train.

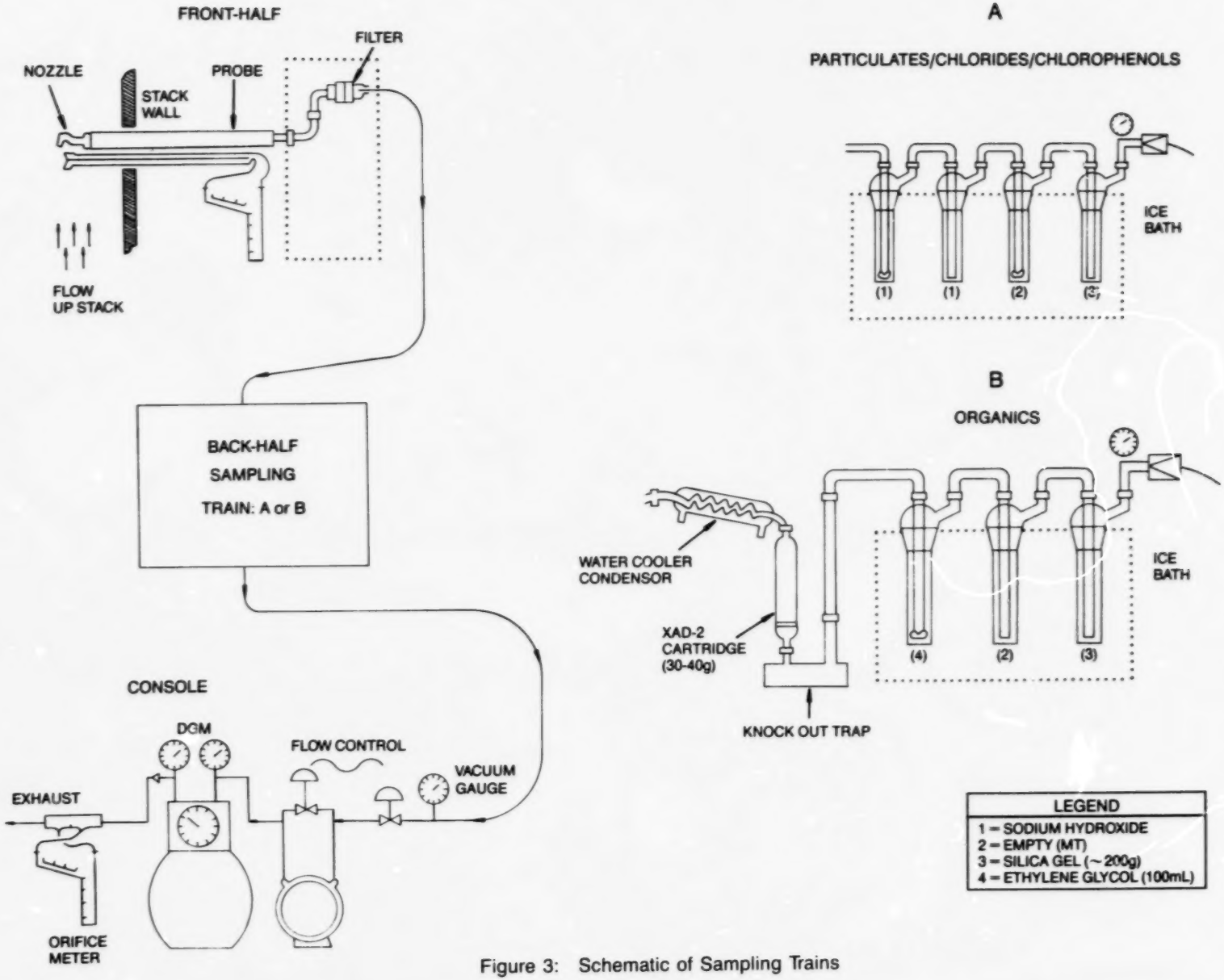


Figure 3: Schematic of Sampling Trains

A Modified EPA Method 5 train was used for the collection of organics (PCDDs, PCDFs, and chlorophenols) by adding a condensor and resin trap after the filter. Following filtration, the stack gases were cooled to less than 20°C. Gaseous organics were then adsorbed in a single adsorbent tube containing 30-40 grams of Amberlite XAD-2 resin. An impinger containing ethylene glycol was inserted downstream of the XAD-2 resin tube to trap any remaining organics. The particulates and back-half absorbing solutions were analyzed for organics.

- o Quench Tank - Waste water samples from the quench tank overflow and ash conveyor end box were collected using American Public Health Association standard method. One litre aliquots from these two sources were taken for analysis.
- o Ash Bunker - Due to physical and practical limitations of the flyash collection system, it was not possible to collect separate samples of fly ash and bottom ash. Therefore, samples of combined ash were collected every 15 minutes from the conveyor discharge. A representative sample of about 24 litres of ash was collected during each run. This was later split for analysis.

Ambient Air

Although two ambient air stations were installed, only the northern station was operated during the test burns as prevailing winds were primarily from the south. Meteorological parameters were measured at the southern air monitoring station.

Total suspended particulates were collected by drawing a controlled amount of ambient air through a pre-weighed glass fibre filter with a nominal porosity of 0.3 microns using a Hi-Vol sampler. The ambient concentration of particulates, expressed in micrograms per cubic metre, is calculated from the ratio of the mass of collected particulates and the volume of air sampled .

Inhalable suspended particulates, commonly known as PM_{10}, with diameters smaller than 10 microns were sampled. A conventional Hi-Vol sampler was equipped with a special aerodynamic inlet that removes particulates larger than 10 microns.

Dioxins/furans and polycyclic aromatic hydrocarbons (PAHs) were collected by using a Hi-Vol PUF sampler which consisted of a particulate filter followed by a PUF absorbent (polyether-type polyurethane foam). The particulate matter and PUF adsorbent were analyzed for dioxins/furans and polycyclic aromatic hydrocarbons.

4.2 Analytical Protocols

- Organics - Organic analyses involved the following basic steps:
  - spiking with surrogate standard solution,
  - solvent extraction of organic constituents from the sample matrix,

- cleanup of raw extract to remove some of the co-extracted, non-target organics, and to separate target organics into fractions for class-specific analysis,
- instrumental analysis by gas chromatography/mass spectroscopy (GC/MS) of each fraction and
- data interpretation and quantification of target organic compounds.

o Hog Fuel - Proximate and ultimate analyses were conducted on hog fuel samples.

Proximate analysis was used to determine the moisture, volatile matter, fixed carbon and ash content. The ASTM analytical procedure was followed.

Ultimate analysis was used to determine the elemental components such as carbon, hydrogen, oxygen and sulphur. The ASTM procedure was followed.

5 TEST DESCRIPTION AND RESULTS

5.1 Test Description

A total of eight test runs were completed for three test conditions.

- Test Condition #1 (Baseline)
  Two test runs were conducted using "clean" hog fuel, specially acquired for the baseline test
- Test Condition #2 (57µg/g CP spike)
  Three test runs were conducted with chlorophenol spiking levels set at about 57 µg/g of hog fuel.
- Test Condition #3 (436 µg/g CP spike)
  Three test runs were conducted with chlorophenol spiking levels set at about 436 µg/g of hog fuel.

Each test run took about four hours. Process data were collated for the corresponding sampling period during each test run. An operational upset occurred during the second baseline test run. Hence, the results for that run are not reported in this summary. Test runs for test conditions #2 and #3 were completed without any significant operating upset. The plant operating parameters, process stream sampling and ambient air monitoring results for test conditions #1, #2 and #3 are shown in Figures 4, 5 and 6, respectively.

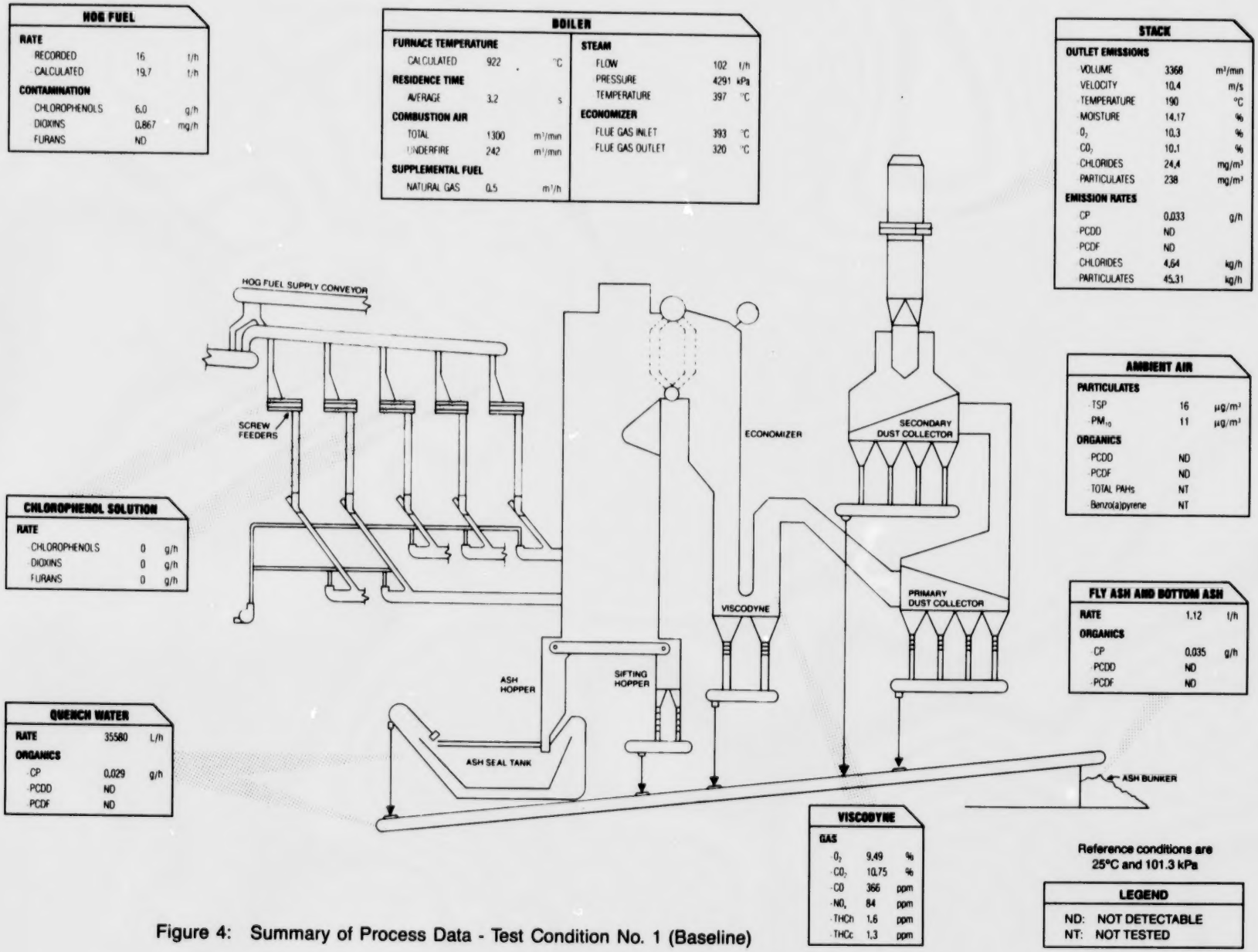
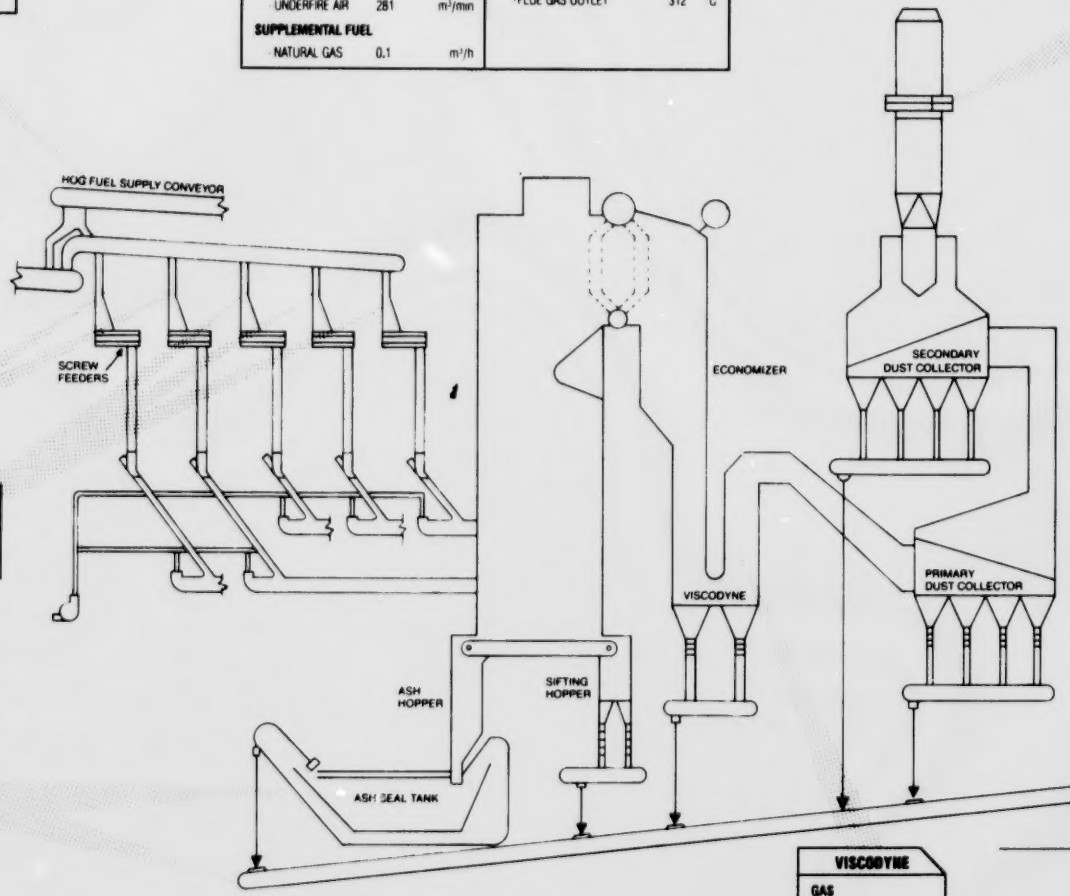


Figure 4: Summary of Process Data - Test Condition No. 1 (Baseline)

HOG FUEL		
RATE		
RECORDED	15.8	t/h
CALCULATED	17.1	t/h
CONTAMINATION		
CHLOROPHENOLS	8.0	g/h
DIOXINS	0.129	mg/h
FURANS	ND	

BOILER					
FURNACE TEMPERATURE			**STEAM**		
CALCULATED	976	°C	FLOW	95	t/h
RESIDENCE TIME			PRESSURE	4268	kPa
AVERAGE	3.3	s	TEMPERATURE	399	°C
COMBUSTION AIR			**ECONOMIZER**		
TOTAL AIR	1116	m³/mn	FLUE GAS INLET	399	°C
UNDERFIRE AIR	281	m³/mn	FLUE GAS OUTLET	312	°C
SUPPLEMENTAL FUEL					
NATURAL GAS	0.1	m³/h			

STACK		
OUTLET EMISSIONS		
VOLUME	3045	m³/mn
VELOCITY	9.4	m/s
TEMPERATURE	191	°C
MOISTURE	14.32	%
O_2	10.8	%
CO_2	9.6	%
CHLORIDES	5.0	mg/m³
PARTICULATES	212	mg/m³
EMISSION RATES		
CP	0.080	g/h
PCDD	ND	
PCDF	ND	
CHLORIDES	0.85	kg/h
PARTICULATES	36.02	kg/h



AMBIENT AIR		
PARTICULATES		
TSP	88	µg/m³
PM_{10}	42	µg/m³
ORGANICS		
PCDD	ND	
PCDF	ND	
TOTAL PAHs	6.51	ng/m³
Benzo(a)pyrene	ND	

CHLOROPHENOL SOLUTION		
RATE		
CHLOROPHENOLS	979	g/h
DIOXINS	0.514	g/h
FURANS	1.502	g/h

FLY ASH AND BOTTOM ASH		
RATE	0.27	t/h
ORGANICS		
CP	0.006	g/h
PCDD	0.018	mg/h
PCDF	ND	

QUENCH WATER		
RATE	35600	L/h
ORGANICS		
CP	0.016	g/h
PCDD	ND	
PCDF	ND	

VISCODYNE		
GAS		
O_2	7.97	%
CO_2	12.40	%
CO	1037	ppm
NO_x	75	ppm
THCh	18.9	ppm
THCc	18.2	ppm

Reference conditions are 25°C and 101.3 kPa

LEGEND
ND: NOT DETECTABLE
NT: NOT TESTED

Figure 5: Summary of Process Data - Test Condition No. 2

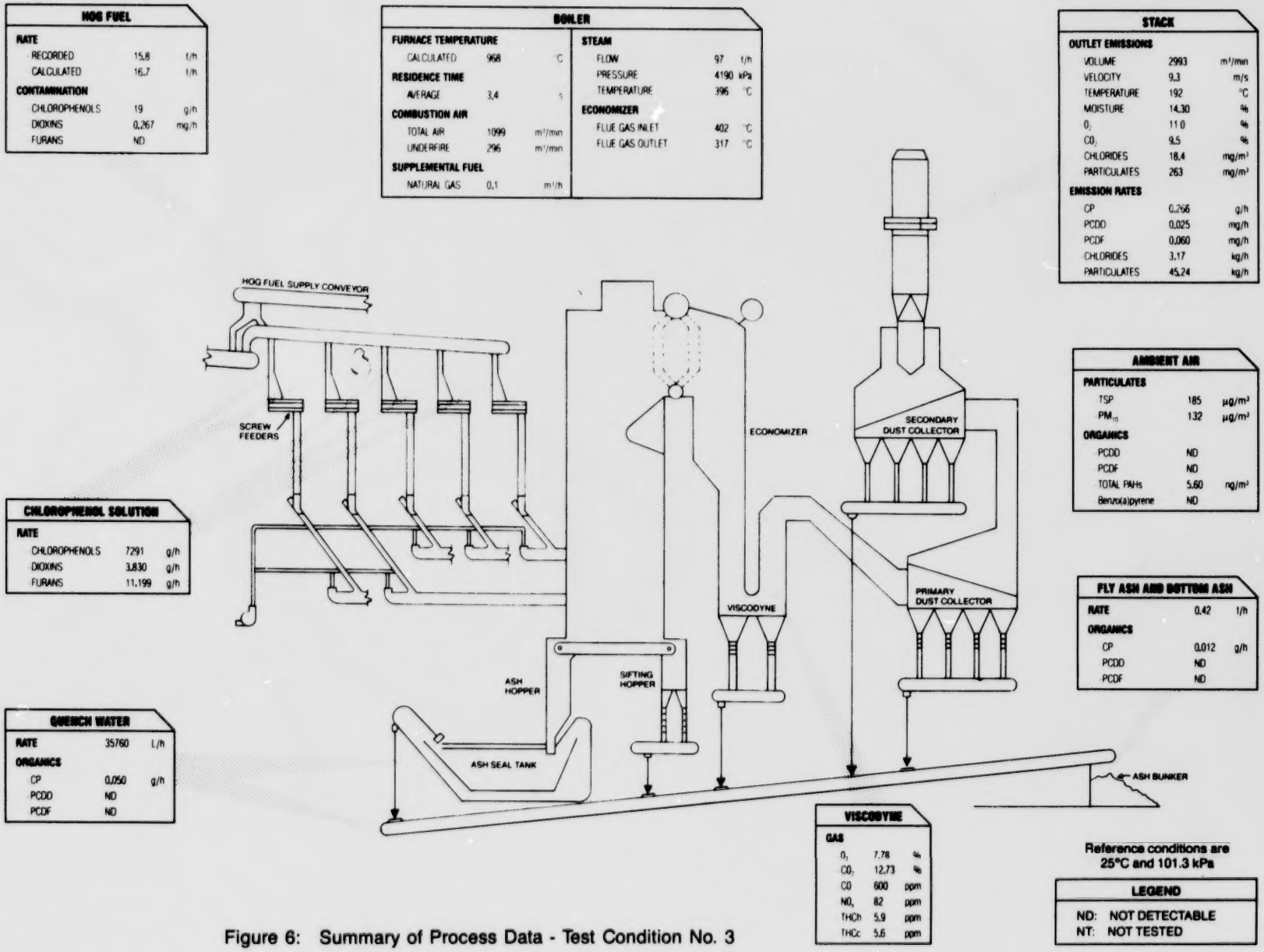


Figure 6: Summary of Process Data - Test Condition No. 3

5.2 Process Stream Sampling Results

The boiler was stabilized at the normal operating output of 95 to 102 tonnes of steam per hour (60% capacity). Operating parameters fluctuated during the baseline test conditions. However, steady-state operation was achieved during test conditions #2 and #3. The results of the three test conditions are summarized in Table 1.

As shown in Table 1, trace quantities of chlorophenols and dioxins were found in hog fuels specially acquired for the project for all three test conditions before chlorophenol solutions were added. However, furans were not detected in any of the hog fuel samples for the three test conditions.

The underfire air ranged from 18.6% to 26.9% of the total air during the test burn. The underfire air should be 50% of the total air according to boiler manufacturer's specifications. The effect of using the recommended combustion air distribution should be considered in future boiler tests.

As expected, the carbon dioxide and oxygen levels correlated well (4) with a correlation coefficient (r^2) of 0.944 as given by the following linear relationship:

$$\%CO_2 = 20.47 - 1.01\%O_2$$

There was a general relationship between total hydrocarbons and carbon monoxide levels. The total hydrocarbon (hot and cold) concentration increased as the carbon monoxide concentration increased in the flue gas. The highest levels of THC were measured during test condition #2. THCh and THCc levels reached 18.9 ppm and 18.2 ppm, respectively, while the CO concentration was 1037 ppm.

5.3 Discharge Sampling Results

Average stack, quench water and ash sampling results are summarized in Table 2 for the three test conditions.

Stack

Manual stack sampling results for particulates varied from 212 to 263 mg/m^3 over the three test conditions.

Trace quantities of dioxins and furans were detected in the stack gas during the high chlorophenol test condition. Average emissions of dioxins and furans were 0.025 mg/h and 0.060 mg/h respectively. The only dioxin detected was octa-chlorinated dibenzo-p-dioxins (O_8CDD) and the only furan detected was tetrachlorinated dibenzofurans (T_4CDF).

Chlorophenol emission rates increased from 0.0030 to 0.080 to

0.266 g/h for the three test conditions respectively. This increase in emissions was proportional to the amount of chlorophenol going into the furnace.

Chloride concentrations in the stack gases ranged from 5.0 to 24.4 mg/m^3. The highest level was recorded during the baseline test condition. After the hog fuel feed rate was stabilized at seventeen tonnes per hour, the chloride content increased from 4.0 mg/m^3 in test condition #2 to 18.4 mg/m^3 in test condition #3.

Quench Water

The average chlorophenol rate in the quench water varied from 0.016 g/h for test condition #2 to 0.050 g/h for test condition #3. During the baseline test condition, when no chlorophenol was added to the hog fuel, the chlorophenol rate in the quench water was 0.029 g/h.

Ash

The average chlorophenol rate in the combined fly ash and bottom ash ranged from 0.006 to 0.035 g/h for the three test conditions. The highest value of 0.035 g/h was recorded during test condition #1 when no chlorophenol solution was added to the hog fuel.

5.4 Ambient Air Monitoring Results

Average ambient air monitoring results and the corresponding meteorological data for background as well as for the three test conditions are listed in Table 3. Total suspended particulates and respirable particulates were sampled for eight hours during test conditions #2 and #3. These results have been converted to 24-hourly averages. TSP results varied between 16 to 148 $\mu g/m^3$, whereas, PM_{10} data ranged from 11 to 106 μ/m^3. The ratio of PM_{10} to TSP varied from 0.48 to 0.74.

Total PAH levels averaged between 5.6 ng/m^3 to 10.24 ng/m^3. One of the most toxic constituents, benzo(a)pyrene, was below the detection limit during test conditions #2 and #3. Dioxins and furans in the ambient air were also below detection limits on the days of the test burns. However, during background monitoring prior to the test burn when normal "as received" hog fuel was burned, 2.42 pg/m^3 of tetrachlorinated dibenzo-p-furans and 0.02 ng/m^3 of benzo(a)pyrene were detected in the ambient air.

During the test burn, winds were primarily southerly. The percentage of on-station winds ranged from 48% for test condition #3 to about 95% for test condition #1. Wind speeds as well as atmospheric stabilty classes were quite variable.

TABLE 1
SUMMARY OF PROCESS DATA

TEST CONDITION SEPTEMBER, 1987	#1 15	#2 19-21	#3 22-24
Hog Fuel			
Recorded (t/h)	16.000	15.800	15.800
Calculated (t/h)	19.700	17.100	16.700
Chlorophenols (g/h)	6.000	8.000	19.000
Dioxins (mg/h)	0.867	0.129	0.267
Furans (mg/h)	ND	ND	ND
Spiking Solution			
Chlorophenols (µg/g)	0.000	57.000	436.000
Chlorophenols (L/h)	0.000	3.070	22.860
Chlorophenols (g/h)	0.000	979.000	7291.000
Dioxins (g/h)	0.000	0.514	3.830
Furans (g/h)	0.000	1.502	11.199
Boiler			
Gas Burner Flow (m/h)	0.500	0.100	0.100
Total Air (m^3/min)	1300.000	1116.000	1099.000
Underfire Air (m^3/min)	242.000	281.000	296.000
Steam			
Flow (t/h)	102.000	95.000	97.000
Pressure (kPa)	4291.000	4268.000	4190.000
Temperature (°C)	397.000	399.000	396.000
Economizer			
Oxygen (%), wet basis	7.000	6.000	6.000
Viscodyne (Flue Gas) *			
Oxygen (%)	9.490	7.970	7.780
Carbon Dioxide (%)	10.750	12.400	12.730
Carbon Monoxide (ppm)	366.000	1037.000	600.000
Nitrogen Oxides (ppm)	84.000	75.000	82.000
Total Hydrocarbon, hot (ppm)	1.600	18.900	5.900
Total Hydrocarbon, cold (ppm)	1.300	18.200	5.600
Quench Water (L/h)	35580.000	35600.000	35760.000
Ash (t/h)	1.120	0.270	0.420

* All volumes expressed on a dry basis and referenced to 25° and 101.3 KPa

TABLE 2
SUMMARY OF SAMPLING RESULTS

TEST CONDITION SEPTEMBER, 1987	#1 15	#2 19-21	#3 22-24
Chlorophenol Spike (µg/g)	0.000	57.000	436.000
Stack Emissions			
In-stack Monitor Particulates (mg/m^3)	99.000	95.000	107.000
Manual Sampling			
Particulates (mg/m^3)	238.000	212.000	263.000
Chlorides (mg/m^3)	24.400	5.000	18.400
Volume (m/min)	3368.000	3045.000	2993.000
Actual Velocity (m/s)	10.400	9.400	9.300
Temperature (°C)	190.000	191.000	192.000
Moisture (%)	14.170	14.320	14.300
Dry Molecular Weight	30.030	29.960	29.960
Oxygen (%)	10.300	10.800	11.000
Carbon Dioxide (%)	10.100	9.600	9.500
Organics (ng/m^3)			
Chlorophenols	164.000	438.000	1482.000
Dioxins	ND	ND	0.140
Furans	ND	ND	0.340
Emission Rates			
Particulates (kg/h)	45.310	36.020	45.240
Chlorides (kg/h)	4.640	0.850	3.170
Chlorophenols (g/h)	0.033	0.080	0.266
Dioxins (mg/h)	ND	ND	0.025
Furans (mg/h)	ND	ND	0.060
Quench Water			
Chlorophenols (g/h)	0.029	0.016	0.050
Dioxins (mg/h)	ND	ND	ND
Furans (mg/h)	ND	ND	ND
Ash			
Chlorophenols (g/h)	0.035	0.006	0.012
Dioxins (mg/h)	ND	0.018	ND
Furans (mg/h)	ND	ND	ND

All volumes expressed on a dry basis and referenced to 25°C and 101.3 kPa.

NT - Not Tested.
ND - Not Detected.

TABLE 3
SUMMARY OF AMBIENT AIR MONITORING RESULTS

TEST CONDITION SEPTEMBER, 1987	Background 11-14	#1 15	#2 19-21	#3 22-24
Ambient Air				
Particulates ($\mu g/m^3$)				
TSP	81.504	16.0	88.00 (71.0)	185.00 (148)
PM_{10}	60.00	11.0	42.00 (34.0)	132.00 (106)
PM_{10}/TSP	0.740	0.69	0.48	0.7
PAHs (ng/m^3) *				
Benzo(a)pyrene	0.020	NT	ND	ND
Total	10.243	NT	6.510	5.6
Dioxins (pg/m^3) *	ND	ND	ND	ND
Furans (pg/m^3)*	2.42	ND	ND	ND
Meteorological Conditions				
Wind Speed (m/s)	1.8	3.50	4.1	1.1
Wind Direction				
(% of time on station)	27.0	95.0	86.0	48.0
Atmospheric Stability	A-F	B-C	C	A

* 24-hr ambient air sampling.
Numbers in paranthesis represent 24-hour averages converted from 8-hour sampling results (6).

NT - Not Tested.
ND - Not Detected.

6 DISCUSSION OF TEST RESULTS

Since the primary objectives of this test program were to evaluate the capability of Northwood's No. 4 power boiler to destroy various levels of chlorophenols, dioxins and furans as well as assess the impact on ambient air quality, this section discusses the results in relation to these objectives.

6.1 Destruction and Removal Efficiency

The capacity of a combustion unit to destroy organics is referred to as its destruction and removal efficiency (DRE). By definition, only the pollutants in the stack gases are considered in the determination of DRE (8) as shown in the following equation:

$$DRE = \frac{W_{in} - W_{out}}{W_{in}} 100\%$$

Where,

W_{in} = Mass feed rate of one principal organic hazardous constituent (POHC) in the feed into the incinerator.

W_{out} = Mass emission rate of the same POHC present in the flue gas.

DRE - Chlorophenols

Chlorophenol material balances for the three test conditions are summarized in Table 4.

All hog fuel used during the test burn contained trace quantities (0.3 to 0.96 µg/g) of residual chlorophenols. Additions of chlorophenols to these residual levels increased the chlorophenol in the hog fuel to 57 µg/g (987 g/h) and 436 µg/g (7310 g/h) for test conditions #2 and #3.

Chlorophenol emissions in the stack gases increased with higher chlorophenol spikes. Although chlorophenol in the hog fuel feed increased from 0.3 µg/g to 436 µg/g or over 1000 times, the chlorophenol emissions in the stack gas increased only tenfold.

The destruction and removal efficiency (DRE) of 99.4500% for chlorophenols was lowest for the baseline condition and ranged from an average of 99.9917 to 99.9963% for the spiked conditions.

TABLE 4
CHLOROPHENOL MATERIAL BALANCE

	Chlorophenol Input	Chlorophenol Output				
TEST CONDITION	Hog Fuel (g/h)	Stack Gas (g/h)	Ash (g/h)	Quench * Water (g/h)	Total (g/h)	DRE** (%)
1	6.000[a]	0.033	0.035	0.029	0.097	99.4500
2	986.667	0.080	0.006	0.016	0.102	99.9917
3	7310.333	0.266	0.012	0.050	0.328	99.9963

TC-Test Condition

* Ash quench water and conveyor water were combined for each test condition. The average chlorophenol content for each condition and the actual water volume for each test run were used to compute the chlorophenol discharge.

* * Excludes chlorophenols in ash and quench water when calculating DRE.

a. chlorophenol present in the hog fuel before spiking

DRE - Dioxins and Furans

Material balances for dioxins and furans are presented in Tables 5 and 6, respectively.

Trace quantities of dioxins were found in all hog fuels including the "clean" hog fuel specially acquired for the baseline test. However, furans were not detected. For test conditions #2 and #3, trace amounts of dioxins and furans in the hog fuels increased proportionally to the quantities of chlorophenol spiking solutions added.

Neither dioxins nor furans were detected in the stack gases during the baseline and low spike conditions.

However, trace quantities of dioxins and furans were detected in the stack gases during the high spike condition. Dioxin emissions were 0.025 mg/h (0.14 ng/m^3) and furans were 0.06 mg/h (0.34 ng/m^3). These emissions are considered to be low and not significant. Using toxicity equivalent factors, the total dioxin/furan concentration is calculated to be 0.034ng/m^3. This is well within the proposed national guideline of 0.500 ng/m^3 @ 11% O_2(7).

Only trace quantities of dioxins (0.018 mg/h as O_8CDD) were detected in ash samples collected during test condition #2.

TABLE 5
DIOXINS MATERIAL BALANCE

	Input	Output			
TEST CONDITION	Hog Fuel (mg/h)	Stack Gas (mg/h)	Ash (mg/h)	Total (mg/h)	DRE (%)
1	0.867*	ND	ND	ND	100
2	514.129	ND	0.018	0.018	100
3	3829.993	0.025	ND	0.025	99.9993

ND - Not Detected
NOTE: No dioxins nor furans were detected in ash quench water.
* Dioxins present in the hog fuel before spiking.

TABLE 6
FURANS MATERIAL BALANCE

	Input	Output			
TEST CONDITION	Hog Fuel (mg/h)	Stack Gas (mg/h)	Ash (mg/h)	Total (mg/h)	DRE (%)
1	0.	ND	ND	ND	100
2	1502.333	ND	ND	ND	100
3	11199.000	0.060	ND	0.060	99.9995

ND - Not Detected
NOTE: No dioxins nor furans were detected in ash quench water.

6.2 Boiler Temperature and Residence Time

Wall temperatures were measured for all test runs at five locations within the furnace. The average wall temperature as measured ranged from 713°C to 743°C for the three test conditions. Since the flue gas temperatures in the center of the fire box are higher than at the walls (II), the average flue gas temperatures for the three test conditions were estimated to be in the range of 763°C to 793°C. Using energy balance calculations, the adiabatic flame temperatures were estimated to vary between 1106°C to 1159°C over the three test conditions. By taking the average of the flue gas temperatures and the estimated adiabatic flame temperatures, the furnace temperatures were determined to be between 922°C to 976°C. The residence time was calculated to range from 3.2 to 3.4 seconds. The residence time and furnace temperature met the general criteria to destroy chlorophenols, dioxins and furans.

6.3 Ambient Air Quality

Dioxins and furans were not detected in any ambient air samples during the test runs. However, 2.4 pg/m^3 of tetrachlorinated dibenzo-p-furans (T_4CDF) were detected during background monitoring on September 11, 1987. These furans likely originated from off-site sources because the wind was predominantly from the north.

The Ontario Ministry of the Environment has provisional ambient air guidelines for dioxins and furans (9). The provisional point of impingement guideline for 1/2-hour average is expressed for mixtures of chlorinated dibenzo dioxins (CDD) and chlorinated dibenzo furans (CDF) as follows:

$$\frac{X}{450} + \frac{Y}{450 \times 50\ pg} = 1$$

where X = concentration of CDDs in air

and Y = concentration of CDFs in air

Since no dioxin was detected, the guideline for 1/2-hour average for CDFs becomes 22,500 pg/m^3. The 24-hour measured value of 2.4 pg/m^3 furans is insignificant when compared to Ontario's provisional guideline for ambient air.

PAHs in ambient air were detected during test conditions 2 and 3, at concentrations of 6.51 ng/m^3 and 5.60 ng/m^3 respectively. Benzo(a)pyrene, one of the most toxic compounds in the PAH group, was not detected during any test run but was detected during the background monitoring and baseline test condition. Benzo(a)pyrene concentrations were 0.03 ng/m^3 and 0.02 ng/m^3, respectively. These concentrations are insignificant when compared to other locations (10):

Location	Benzo(a)pyrene (ng/m^3)
Northwood Test Burn	0.02 to 0.03
Toronto, Ontario	0.3
Montreal, Quebec	0.6
Sydney, Nova Scotia	1.3
Whitehorse, Yukon	8.9
Kitimat, British Columbia	14.1

The lowest concentration (11 µg/m^3) of total suspended particulates in ambient air was measured during test condition #1. The highest concentration of 185 µg/m^3 was measured for an eight hour sampling period in the high spike condition. This eight hour concentration converts to 148 µg/m^3 for a 24-hour period (6). This meets the British Columbia level "A" objective for particulates of 150 µg/m^3 for 24 hours. The highest PM_{10} concentration of 132 µg/m^3 for an eight-hour period was also measured during the high spike condition. This converts to 106 µg/m^3 for a 24-hour period (6). This meets the US EPA standard of 150 µg/m^3 for PM_{10} for a 24-hour sampling period.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Based on the results of the eight test runs with the boiler operating at 60% capacity and combustion temperatures higher than 922°C and residence time of over 3.2 seconds, the following conclusions can be made with respect to Northwood's No. 4 power boiler:

1. The boiler was effective in destroying chlorophenols. Destruction and removal efficiencies (DREs) for chlorophenols ranged from 99.9917% to 99.9963% during the low and high spike conditions respectively.

2. The boiler was effective in destroying dioxins and furans. These compounds were not detected in the stack gas emissions during the baseline and low spike (57 µg/g) conditions (57 µg of chlorophenols per gram of hog fuel). Trace quantities of dioxins and furans were detected in stack gases for two test runs of the high spike condition (436 µg/g). The lowest destruction and removal efficiency (DRE) of dioxins and furans was 99.9993%.

   Trace quantities of dioxins and furans were found in the

bottom ash during the low and high spike conditions. Dioxins and furans in ash quench water were below detection limits for all test conditions.

3. Low levels of chlorophenols and dioxins were detected in "clean" hog fuel specially acquired for the project.

4. Stack particulate emissions did not exceed the provincial level "B" objective of 460 mg/m^3 for power boilers. However, level "A" objective of 230 mg/m^3 was exceeded in two test runs of the high spike condition.

5. Total suspended particulates in ambient air met the provincial level "A" ambient air quality objective of 150 $\mu g/m^3$ for 24 hours. The inhalable particulate concentration (PM_{10}) in ambient air met the US EPA standard of 150 $\mu g/m^3$ for 24 hours.

6. Dioxins, furans and one of the most toxic polycyclic aromatic hydrocarbons, benzo(a)pyrene, were below detection limits in the ambient air during the test runs when chlorophenol solutions were added to the hog fuels. The trace quantities of furans and benzo(a)pyrene detected in the ambient air during background monitoring are thought to originate from sources other than the power boiler.

7.2 Recommendations

Based on experience gained and results obtained from this test program, the following recommendations are proposed:

1. Further test burns should be conducted to determine dioxins/furans emissions from a power boiler at a coastal mill. Hog fuel from logs transported in sea water contains substantially higher chloride concentrations than hog fuel at interior mills. As chlorides tend to favor the formation of dioxins, the possible effects of chlorides on the destruction of organics in the power boiler should be assessed.

2. Test burns should be conducted at a minimum of 90% boiler steam capacity. Operating at a higher capacity reduces the residence time of the gases in the combustion zone and this may affect the destruction efficiency.

3. Further studies should be carried out to determine the variation of chlorophenol and dioxin concentrations in normal "as received" hog fuels.

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APPENDIX A
Symbols, Abbreviations and Conversion Factors

Prefix	Symbol	Multiplication Factor		Exponent
mega	M	1 000 000	=	10^6
kilo	k	1 000	=	10^3
hecto	h	100	=	10^2
deca	da	10	=	10^1
unit	-	1	=	10^0
centi	c	0.01	=	10^{-2}
milli	m	0.001	=	10^{-3}
micro	μ	0.000 001	=	10^{-6}
nano	n	0.000 000 001	=	10^{-9}
pico	p	0.000 000 000 001	=	10^{-12}

Symbol	Unit	Conversion
Mass/Weight		
g	gram	-
tonne	metric tonne	1 tonne = 1Mg
lb	pound	1 pound = 453.592g
Length		
m	metre	-
ft	foot	1 foot = 0.3048m
Volume		
L	litre	-
m^3	cubic metre	$1m^3$ = 1000L
cm^3	cubic centimetre	
ft^3	cubic foot	1 ft^3 = $0.02832m^3$
Time		
s	second	-
m (min)	minute	1 min = 60s
h (h)	hour	1 h = 3600s

Temperature

°C	degree Celsius	-
°F	degree Fahrenheit	-

Pressure

btu	British Thermal Units	-
Pa	Pascal	1 Pa = 10^5bar
psig	pounds per square inch	-

Energy

J	Joules	1 J = 9.4845x10^4btu

Speed

rpm	revolutions per minute

Acronyms

EPA	Environmental Protection Agency
EPS	Environmental Protection Service
EC	Environment Canada
BC MOE	British Columbia Ministry of Environment
APHA	American Public Health Association

Sampling and Analytical Terminology

GC	Gas Chromatography
MS	Mass Spectrometry
ECD	Electron Capture Detector
MM5	Modified Method 5
QA/QC	Quality Assurance/Quality Control
CMS	Continuous Monitoring System
PM_{10}	Particulate Matter (diameter less than 10 microns)
TSP	Total Suspended Particulates
PUF	Polyurethane Foam
ID	Internal Diameter
STP	Standard Temperature and Pressure
ND	Not Detected
NT	Not Tested
THCc	Total Hydrocarbons (cold)

THCh	Total Hydrocarbons (hot)
Compounds	
PCBs	Polychlorinated Biphenyls
PCDDs	Polychlorinated Dibenzo-p-dioxin
PCDFs	Polychlorinated Dibenzofuran
PCPs	Pentachlorophenols
PAHs	Polycyclic Aromatic Hydrocarbons
TeCPs	Tetrachlorophenols
THCs	Total Hydrocarbons
CPs	Chlorophenols
CO	Carbon Monoxide
CO_2	Carbon Dioxide
NOx	Nitrogen Oxides
O_2	Oxygen
NaOH	Sodium Hydroxide
T4CDDs	Tetrachlorinated dibenzo-p-dioxins
P5CDDs	Pentachlorinated dibenzo-p-dioxins
H6CDDs	Hexachlorinated dibenzo-p-dioxins
H7CDDs	Heptachlorinated dibenzo-p-dioxins
O8CDFs	Octachlorinated dibenzofurans

Miscellaneous	
ppm	parts per million
°	degree (temperature)
DRE	Destruction and Removal Efficiency
vol	volume
Hi-Vol	High Volume
M	Molar
TR	Test Run
TC	Test Condition
TB	Test Burn

APPENDIX B

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